

A new formation model for M32: A threshed early-type spiral?

Kenji Bekki and Warrick J. Couch

School of Physics, University of New South Wales, Sydney 2052, Australia

Michael J. Drinkwater

School of Physics, University of Melbourne, Victoria 3010, Australia

and

Michael D. Gregg

Department of Physics, University of California at Davis, Davis, CA 94550. USA

ABSTRACT

The origin of the closest compact elliptical galaxy (cE) M32 is a longstanding problem of galaxy formation in the Local Group. Our N-body/SPH simulations suggest a new scenario in which the strong tidal field of M31 can transform a spiral galaxy into a compact elliptical. As a low luminosity spiral galaxy plunges into the central region of M31, most of the outer stellar and gaseous components of its disk are dramatically stripped due to M31's tidal field. The central bulge component, on the other hand, is just weakly influenced by the tidal field owing to its compact configuration, and retains its morphology. M31's strong tidal field also induces rapid gas transfer to the central region, triggers a nuclear starburst, and consequently forms the central high density and more metal-rich stellar populations with relatively young ages. Thus, in this scenario, M32 was previously the bulge of a spiral tidally interacting with M31 several Gyr ago. Furthermore, we suggest cEs like M32 are rare, the result of both the rather narrow parameter space for tidal interactions which morphologically transform spirals into cEs and the very short time scale ($< \text{a few } 10^9 \text{ yr}$) for cEs to be swallowed by their giant host galaxies (via dynamical friction) after their formation.

Subject headings: galaxies: bulges — galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: interactions

1. Introduction

Andromeda’s (M31) closest companion, M32, has long served as a laboratory that can provide valuable information not only on the nature of stellar populations of low mass elliptical galaxies but also on the detailed structure of their nuclei (e.g., Davidge 2000; van den Bergh 2000). M32 is classified, morphologically, as a compact elliptical (cE) that has rather high central surface brightness (\sim four orders of magnitude higher than that of typical spheroidals of comparable total luminosity), a truncated de Vaucouleurs profile, and solar-like metallicity (e.g., Kormendy 1985; Nieto & Prugniel 1987). M32-like cEs are observed to be located almost exclusively in the vicinity of bright galaxies (Nieto & Prugniel 1987) and generally considered to be very rare objects both in the field and in clusters (Kormendy 1985; Ziegler & Bender 1998; Drinkwater & Gregg 1998). A large number of previous spectroscopic studies aimed at placing strong constraints on M32’s star formation history have suggested the existence of young stellar populations with ages of several Gyr (e.g., O’Connell 1980; Burstein et al. 1984; Rose 1984; Bica, Alloin, & Schmidt 1990; Vazdekis & Arimoto 1999; del Burgo et al. 2001), though recent studies have argued that there is no clear evidence supporting M32’s relatively recent star formation (e.g., Cole et al. 1998; Renzini 1998). The most recent spectroscopic studies have suggested M32 has relatively young (\sim several Gyr old) stellar populations (e.g., del Burgo et al. 2001; Davidge et al. 2001; See Davidge 2000 and van den Bergh 2000 for a recent review).

The origin of the high surface brightness of cEs and radially-limited luminosity profiles has been discussed mostly in the context of the tidal effects of massive galaxies close to them (King 1962; Faber 1973; Nieto & Prugniel 1987; Burkert 1994). For example, Faber (1973) first proposed that M32 was previously the inner high-density region of a low-luminosity elliptical galaxy with the outer part stripped by M31 tidal field. Burkert (1994) proposed an alternative scenario that M32 formed through starbursts and the subsequent violent gravitational collapse in M31’s vicinity, where its strong tidal field can induce very efficient violent relaxation in the M32 collapse. It is, however, still controversial how these models can provide a plausible explanation for the observationally suggested intermediate-age (~ 5 Gyr) stellar populations in M32.

Through numerical simulations, we have investigated how M31’s strong tidal field affects the chemical and dynamical evolution of a gas-rich spiral plunging into the central region of M31, demonstrating that dissipative tidal interactions can dramatically transform a spiral into a cE such as M32. In this scenario, a gas-rich disk galaxy with a compact bulge, captured by M31 several Gyr ago, loses a significant fraction of its initial disk mass during dynamical interaction with M31 through tidal stripping. The central bulge component, on the other hand, survives, retaining its compactness. Although this “threshed spiral” (for

the concept of galaxy “threshing”, see Bekki, Couch, & Drinkwater 2001; hereafter BCD) scenario has already been speculated on by several authors (e.g., Nieto 1990; van den Bergh 2000), the present numerical study is the first to demonstrate that this scenario is realistic and viable for the formation of M32. This scenario is in a striking contrast to the canonical one (Wirth & Gallagher 1984; Kormendy 1985) in which cEs like M32 form the faint branch of the normal elliptical sequence.

2. Model

We consider a gas-rich disk galaxy with a bulge, orbiting a massive disk galaxy with structural and kinematical properties similar to those of M31. We adopt TREESPH codes described in Bekki (1995) for hydrodynamical evolution of galaxies. We use the disk model of Fall-Efstathiou (1980) with a dark-halo-to-disk mass ratio equal to 4 for M32’s progenitor disk. The total mass (M_d) and the size of the exponential disk (R_d) are $4.0 \times 10^9 M_\odot$ and 4.5 kpc (scale length of 0.9 kpc), respectively. The gas mass fraction is set to be 0.1 and an isothermal equation of state is used for the gas with a temperature of 7.3×10^3 K, corresponding to a sound speed of 10 km s^{-1} . Star formation is modeled according to the Schmidt law (Schmidt 1959) with an exponent of 1.5. The central bulge is modeled by the Plummer model (Binney & Tremaine 1987) with total mass $2.0 \times 10^9 M_\odot$, corresponding to a bulge mass fraction of 0.33 and scale length of 0.25 kpc. The total number of particles used for each model are 20,000 for collisionless particles and 5,000 for gaseous ones.

The orbit of the spiral is assumed to be influenced only by the *fixed* gravitational potential of M31, having three components: a dark matter halo, a disk, and a bulge. We assume a logarithmic dark matter halo potential,

$$\Phi_{\text{halo}} = v_{\text{halo}}^2 \ln(r^2 + d^2), \quad (1)$$

a Miyamoto-Nagai (1975) disk,

$$\Phi_{\text{disk}} = -\frac{GM_{\text{disk}}}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}} \quad (2)$$

and a spherical Hernquist (1990) bulge

$$\Phi_{\text{bulge}} = -\frac{GM_{\text{bulge}}}{r + c}, \quad (3)$$

where r is the distance from the center of M31, $d = 12 \text{ kpc}$, $v_{\text{halo}} = 131.5 \text{ km s}^{-1}$, $M_{\text{disk}} = 1.3 \times 10^{11} M_\odot$, $a = 6.5 \text{ kpc}$, $b = 0.26 \text{ kpc}$, $M_{\text{bulge}} = 9.2 \times 10^{10} M_\odot$, and $c = 0.7 \text{ kpc}$. This

reasonable set of parameters gives a realistic rotation curve for M31 with a rotation speed of 260 km s^{-1} at 26 kpc.

The center of M31 is always set to be $(x, y, z) = (0, 0, 0)$ whereas the initial position and velocity of the spiral are $(x, y, z) = (0, 0, r_{\text{in}})$ and $(V_x, V_y, V_z) = (0, V_{\text{in}}, 0)$, respectively. By changing these two parameters r_{in} and V_{in} , we investigate how the transformation process from spirals into cEs depends on their orbits. Although we have investigated models with a variety of different r_{in} and V_{in} , we mainly describe here the results of a ‘standard’ model with $r_{\text{in}} = 12 \text{ kpc}$ and $V_{\text{in}} = 142 \text{ km s}^{-1}$ (corresponding to $0.5V_c$, where V_c is a circular velocity of M31 at this radius). Figure 1 shows the orbit with respect to M31 and the final mass distribution for the simulated M32 in the standard model. We choose this nearly polar orbit from the most likely M32 orbit by Cepa & Beckman (1988).

In the following, our units of mass, length, and time are $2.0 \times 10^8 M_\odot$, $7.94 \times 10^2 \text{ pc}$, and $2.36 \times 10^7 \text{ yr}$, respectively. Parameter values and final morphologies for each model are summarized in Table 1. The fourth column gives pericenter distance (r_p) for each model. The fifth describes the final morphological properties after 32 time units (corresponding to 0.76 Gyr): ‘cE’ indicates a remnant with the outer disk completely stripped yet the bulge largely unaffected, ‘S0’ the case where both the outer disk and bulge survive yet the disk is partly stripped (thus becoming a smaller disk) and rather thickened owing to dynamical heating, ‘no remnant’ where both disk and bulge components are tidally destroyed, and ‘Sa’ the case where the spiral keeps its initial morphology.

3. Results

As the spiral approaches the pericenter of its orbit for the first time ($T = 0.09 \text{ Gyr}$), the strong tidal field of M31 stretches the stellar disk along the direction of the spiral’s orbit and consequently tidally strips the stars of the disk (see Figure 2). The disk gradually loses a large number of its stars from its outer part ($0.09 < T < 0.38 \text{ Gyr}$) and finally loses most of its outer stellar disk ($T = 0.47 \text{ Gyr}$): The spiral can keep only stars initially in the central region where the bulge gravitational field dominates. Although galaxy-scale star formation is triggered by the tidal interaction, the outer new stellar component is also tidally stripped away from the spiral, and consequently only the central starburst component survives. The central bulge, on the other hand, is just weakly influenced by the tidal force because of its compact configuration during the tidal destruction of the outer spiral.

Figure 3 shows that a significant fraction ($\sim 59\%$) of the stellar disk is stripped by the M31 strong tidal field within 0.75 Gyr. Thanks to its strongly self-gravitating nature,

the bulge loses only a small amount ($\sim 19\%$) of mass and thus can keep its compact morphology during its tidal interaction with M31. The total mass of new stars within the central 5 kpc suddenly becomes larger early in the tidal interaction ($T < 0.2$ Gyr) because rapid gaseous inflow to the central region causes efficient star formation. However the mass fraction of the stellar disk and that of the bulge do not so significantly change within the bulge-dominated region ($r < 2$ kpc): The fractional mass decreases (increases) from 0.55 (0.45) to 0.33 (0.59) for the disk (bulge). The fractional mass of the new stellar component, on the other hand, greatly increases to reach 0.08, which implies that the simulated M32 can have a remarkable fraction of young stars for an elliptical galaxy.

The tidal distortion forms non-axisymmetric structures (spirals and bar), induces efficient gaseous dissipation in the shocked gaseous region with the subsequent rapid radial gas transfer to the central region, which consequently triggers a massive starburst. This starburst trigger mechanism is essentially the same as that already demonstrated by Noguchi & Ishibashi (1986) for the case of a galaxy-galaxy interaction. The maximum star formation rate is $9.5 M_{\odot} \text{ yr}^{-1}$ (at $T=0.07$ Gyr) corresponding to ~ 31 times higher than the mean star formation rate of the isolated disk model ($0.31 M_{\odot} \text{ yr}^{-1}$). Owing to this starburst, a significant fraction of gas (64 % corresponding to 2.2 times larger than the isolated model case) is consumed by the star formation, and most of the remaining gas is tidally stripped away from the disk. Owing to chemical evolution associated with this efficient star formation, the bulge finally has a young stellar population with a mean metallicity of $[\text{Fe}/\text{H}]=+0.1$ and a radial metallicity gradient. The central, more metal-rich components and the gradient may well be responsible for M32 being observed to have stronger CN and Mg absorption for its luminosity (Faber 1973) and partly associated with the origin of the radial variations of total AGB luminosity observed in M32 (Davidge et al. 2001).

The present parameter study also provides a clue to the problem as to why cEs like M32 are apparently so rare (see Table 1). For Model 3, with smaller r_{in} (12 kpc) and smaller V_{in} (28 km s^{-1}), both the bulge and stellar disk components completely disintegrate during the tidal interaction and, accordingly, no remnant is left. On the other hand, for Model 5 with smaller r_{in} (12 kpc) and larger V_{in} (255 km s^{-1}), the tidal field can only heat up the stellar disk in the vertical direction and consequently transform a spiral into an S0 with a thick disk. These results imply that both V_{in} and r_{in} should be within a certain range and thus that the pericenter, r_{p} , of the orbit of a spiral plunging into M31 should be within a certain range ($r_{\text{p}} \sim \text{several kpc}$). The results of Models 6, 7, and 8 confirm this, and accordingly the present results strongly suggest that the parameter space for the formation of cEs like M32 is rather narrow. Furthermore, our results demonstrate that S0s can be formed from spirals with bulges owing to tidal interaction with their bright host galaxies

(see Models 5 and 7).

4. Discussion and conclusion

A new type of sub-luminous and extremely compact “dwarf galaxy” (the so-called “ultra-compact dwarf”, referred to as UCD) has been recently discovered in an “all-object” spectroscopic survey centred on the Fornax Cluster (Drinkwater et al. 2000a, b). Drinkwater & Gregg (1998), however, did not find any promising candidates of cEs (such as NGC 4486B observed in the vicinity of M87) in the same cluster environment. These recent observations have raised the following question on the origin of two different types of compact galaxy, UCDs and cEs (Drinkwater et al. 2000a; BCD): Are there any physical relationships between these two types? BCD have demonstrated that the strong tidal field of a bright elliptical can transform a nucleated dwarf (dEn) into an UCD owing to the dramatic stripping of the outer stellar envelope: Only the central compact nucleus can manage to survive after this “galaxy threshing”. This result combined with the present numerical results therefore suggests that the origin of the difference in physical properties between UCDs and cEs is due to the difference in morphological types (i.e., spirals versus dEn) of the precursor galaxies destined to suffer from “galaxy threshing”. This explanation is consistent with the observational fact that both UCDs and cEs are located preferentially in the vicinity of bright galaxies, where “galaxy threshing” works more readily. Although no UCD’s are currently known around M31, there may be one in its future. Zinnecker & Cannon (1986) recognized that the star-forming dwarf companion of M31 NGC 205 is comparable to Virgo cluster nucleated dE galaxies; if its orbit with respect to M31 is rather eccentric, it will be threshed by M31 and leave an UCD or an ω Centauri-like peculiar globular cluster (e.g., G1) with M_B approximately -12mag around M31.

A direct observational test for confirming the proposed “threshed spiral” scenario is to investigate whether (1) some of M31’s halo globular clusters (GCs) show peculiarities in their spatial distribution and kinematics, such as clumping or streams along M32’s orbit and retrograde orbital rotation (with respect to M31) similar or nearly identical to M32’s retrograde orbit suggested by Cepa & Beckman (1988), and (2) there are any stellar and/or gaseous streams or sub-structures *well outside* the present orbital plane of M32. M32 is observed to have no GCs (Harris 1991), whereas it should have $\sim 10\text{--}20$ given its luminosity (van den Bergh 2000). This fact probably implies that most of the GCs initially associated with M32’s bulge are tidally stripped from M32 at the epoch of M32 formation (e.g., van den Bergh 2000). Accordingly, if future photometric and spectroscopic studies, deriving *both* the detailed two-dimensional GC distribution and the radial velocity of each

GC with respect to M31, find some GCs located previously on M32’s orbit, these would strengthen the possibility of the threshed scenario. Furthermore, the present study predicts that tidally stripped stars can be distributed well outside M32’s present orbit. Such low surface brightness stellar components (e.g., the so-called “spaghetti” structures observed in the Galaxy; Morrison et al. 2000) *with old and intermediate ages* may well be observed as sub-structures in M31’s stellar halo if they are projected onto the sky. Therefore, future large systematic surveys of M31’s stellar halo light distribution via wide-field CCD imagery on 8m-class telescopes (e.g., SUBARU with Suprime-Cam) will assess the validity of the proposed “threshed spiral” scenario.

We are grateful to the anonymous referee for valuable comments, which contribute to improve the present paper. The authors acknowledge the financial support of the Australian Research Council throughout the course of this work. MDG acknowledges support by the National Science Foundation under Grant No. 9970884.

REFERENCES

- Bekki, K. 1995, MNRAS, 276, 9
- Bekki, K., Couch, W. J., & Drinkwater, M. J., 2001, ApJ, 552, 105L (BCD)
- Bica, E., Alloin, D., & Schmidt, A. A., 1990, A&A, 228, 23
- Binney, J., & Tremaine, S., 1987 in Galactic Dynamics.
- Burkert, A. 1994, MNRAS, 266, 877
- Burstein, D., Faber, S. M., Gaskell, C. M., & Krumm, N. 1984, ApJ, 287, 586
- Cepa, J., & Beckman, J. E. 1988, A&A, 200, 21
- Cole, A. A. et al. 1998, ApJ, 505, 230
- Davidge, T. J. 2000, PASP, 112, 1177
- Davidge, T. J., Rigaut, F., Chun, M., Brandner, W., Potter, D., Northcott, M., & Graves, J. E. 2001, preprint (astro-ph/0010312)
- del Burgo, C., Peletier, R. F., Vazdekis, A., Arribas, S., & Mediavilla, E. 2001, MNRAS, 321, 227
- Drinkwater, M., & Gregg, M. 1998, MNRAS, 296, L15
- Drinkwater, M. J., Phillipps, S., Jones, J. B., Gregg, M. D., Deady, J. H., Davies, J. I., Parker, Q. A., Sadler, E. M., & Smith, R. M. 2000a, A&A, 355, 900
- Drinkwater, M. J., Jones, J. B., Gregg, M. D., & Phillipps, S. 2000b, PASA, in press
- Faber, S. M. 1973, ApJ, 179, 423
- Fall, S. M., & Efstathiou, G. 1980, MNRAS, 193, 189
- Harris, W. E., 1991, ARA&A, 29, 543
- Hernquist, L. 1990, ApJ, 356, 359
- King, I. R. 1962, AJ, 67, 471
- Kormendy, J. 1985, ApJ, 295, 73
- Miyamoto, M.; Nagai, R. 1975, PASJ, 27, 533

- Morrison, H. L., Mateo, M., Olszewski, E. W., Harding, P., Dohm-Palmer, R. C., Freeman, K. C., Norris, J. E., Morita, Miwa. 2000, *AJ*, 119, 2254
- Nieto, J.-L., 1990, in Wielen R., ed. *Dynamics and Interactions of Galaxies*, Springer, Berlin. p258
- Nieto, J.-L., & Prugniel, P. 1987, *A&A*, 186, 30
- O’Connell, R. W. 1980, *ApJ*, 236, 430
- Renzini, A. 1998, *AJ*, 115, 2459
- Rose, J. A., 1985, *AJ*, 90, 1927
- Schmidt, M. 1959, *ApJ*, 344, 685
- van den Bergh, S. 2000, *The Galaxies of the Local Group*
- Vazdekis, A., & Arimoto, N. 1999, *ApJ*, 525, 144
- Wirth, A., & Gallagher, J. S. III. 1984, *ApJ*, 282, 85
- Ziegler, B. L., & Bender, R. 1998, *A&A*, 330, 819
- Zinnecker, H., Cannon, R. D., 1986, in *Star Forming Dwarf Galaxies and Related Objects*, eds. D. Kunth, T.X. Thuan, J. Tran Thanh Van., p155

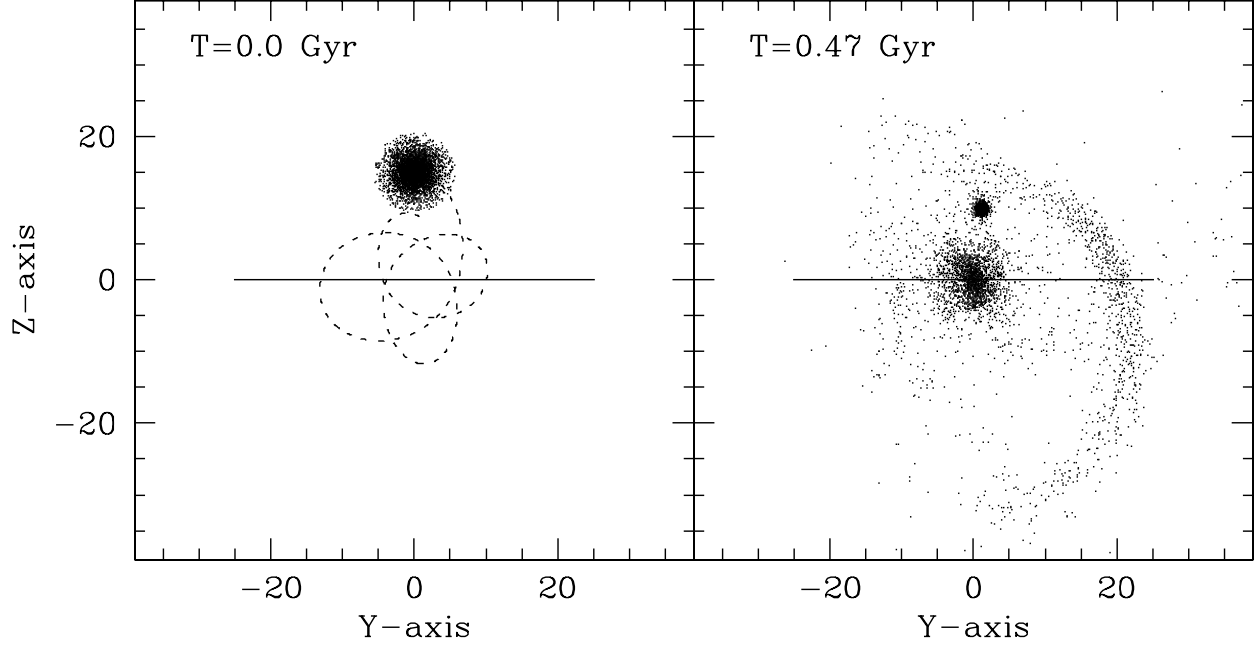


Fig. 1.— Initial (*left*) and final (*right*) mass distribution of the simulated spiral projected onto the y - z (face-on) plane for the “standard” model. The orbital evolution of the spiral with respect to the center of M31 is also given by *dashed* line in the left panel in order that the dynamical evolution can be seen more clearly. The center of M31 is set to be always $(x,y,z) = (0,0,0)$ and the initial and final positions of the spiral are $(x,y,z) = (1.3,0,15.0)$ and $(1.0,1.3,8.5)$, respectively. The scale is given in our units (0.8 kpc) and thus each frame measures 62 kpc on a side. The initial position and size of M31’s disk are given by a *solid* line for each panel. Note that owing to the strong tidal field of M31, a significant fraction of the outer stellar disk of the spiral (both old and young stars) is stripped away at $T = 0.47$ Gyr: only a compact bulge can be seen at $(x,y,z) = (1.0,1.3,8.5)$ (The apparently high surface density clumping of stars around $(x,y,z) = (0,0,0)$ is due to tidal debris of the spiral). Note also that without including the effects of dynamical friction in the model, the apocenter distance of the orbit becomes smaller owing to the mass loss of the spiral preferentially at its pericenter. The surface brightness of the tidal debris is estimated to be ~ 26 mag arcsec $^{-2}$ in V -band for the M32’s distance of 760 kpc from the Galaxy.

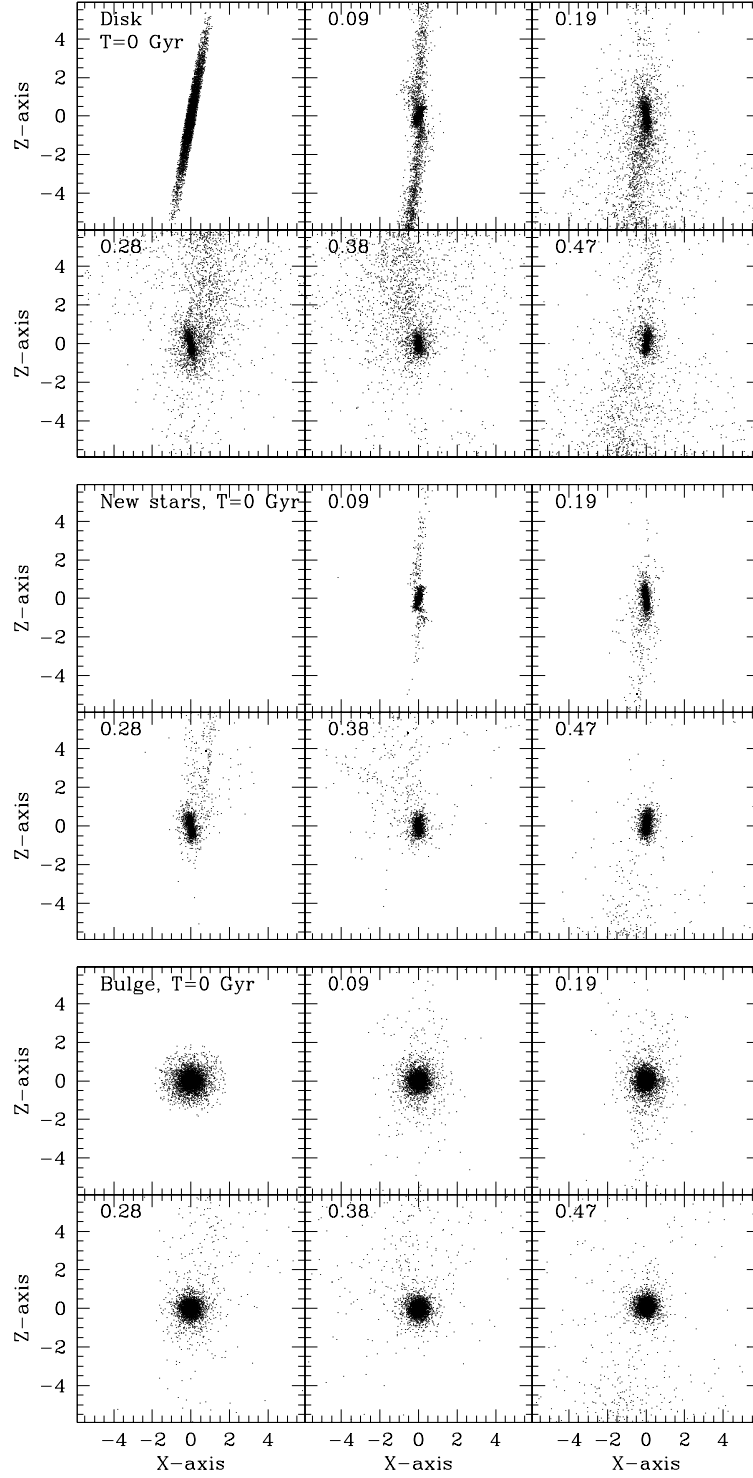


Fig. 2.— Morphological evolution projected onto the x - z plane (edge-on) for the stellar disk (top six panels), the new stars formed from gas (middle), and the bulge (bottom) in the simulated spiral. The time indicated in the upper left corner of each frame is given in Gyr and each frame measures 9.4 kpc on a side.

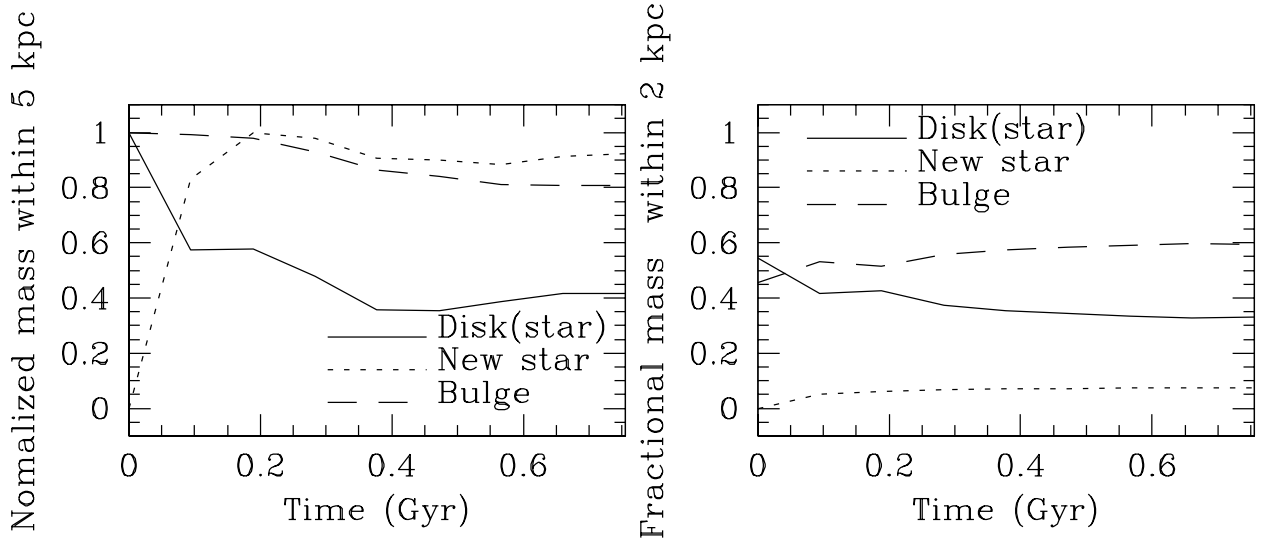


Fig. 3.— *Left*: Time evolution of normalized mass within the central 5 kpc (corresponding to the disk size of the spiral) for the stellar disk (solid), the new stars formed from gas (dotted), and the bulge (short-dashed) in the simulated spiral. Here the mass of the stellar disk and that of the bulge are normalized by their initial masses whereas that of the new stars is normalized by its maximum mass within the 5 kpc. *Right*: Time evolution of fractional mass within the central 2 kpc (corresponding to $\sim 2\times$ larger than the initial size of the bulge) for the stellar disk (solid), the new stars (dotted), and the bulge (short-dashed).

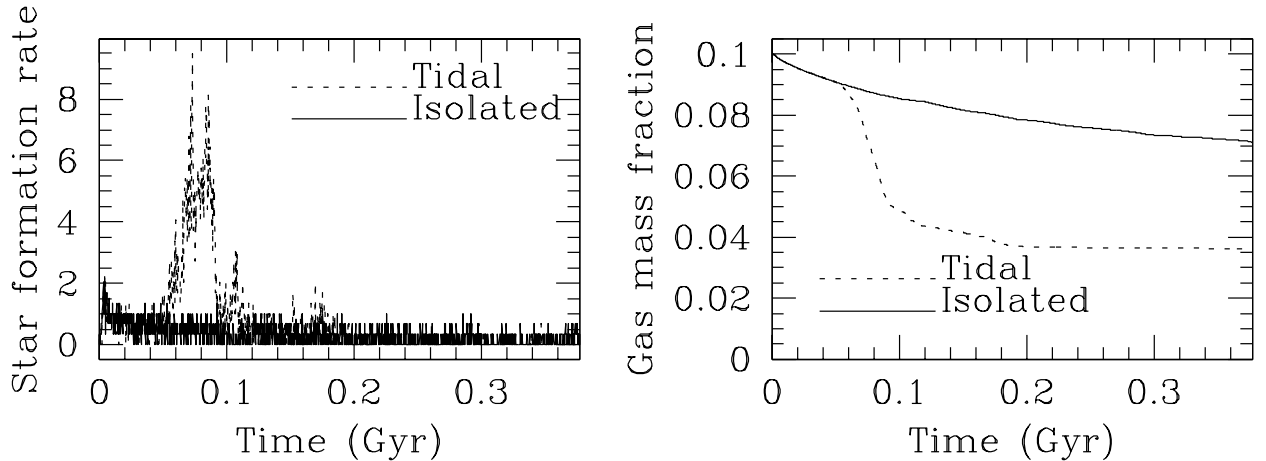


Fig. 4.— The time evolution of star formation in units of $M_{\odot} \text{ yr}^{-1}$ (*left*) and that of gas mass fraction (*right*) for the isolated model (solid) and for the standard model (dotted, represented as “tidal” model).

Table 1. Results of different models of tidal interaction between a spiral galaxy and M31

model number	r_{in} (kpc)	V_{in} (km s $^{-1}$)	r_{p} (kpc)	final morphology	comments
1	12	142	4.5	cE	standard model
2	–	–	–	Sa	isolated model
3	12	28	0.5	no remnant	
4	12	212	8.8	cE	
5	12	255	10.7	S0	
6	24	50	2.2	cE	
7	24	188	15.0	S0	
8	24	376	24.0	Sa	circular orbit